A $G$-family of quandles and handlebody-knots

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We introduce the notion of a $G$-family of quandles and use it to construct invariants for handlebody-knots. Our invariant can detect the chiralities of some handlebody-knots including unknown ones. This is a joint work with Atsushi Ishii, Yeonhee Jang and Kanako Oshiro ([8]).

1 Handlebody-links

A handlebody-link is a disjoint union of handlebodies embedded in the 3-sphere $S^3$. Two handlebody-links are equivalent if there is an orientation-preserving self-homeomorphism of $S^3$ which sends one to the other. A spatial graph is a finite graph embedded in $S^3$. Two spatial graphs are equivalent if there is an orientation-preserving self-homeomorphism of $S^3$ which sends one to the other. When a handlebody-link $H$ is a regular neighborhood of a spatial graph $K$, we say that $K$ represents $H$, or $H$ is represented by $K$. In this paper, a trivalent graph may contain circle components. Then any handlebody-link can be represented by some spatial trivalent graph. A diagram of a handlebody-link is a diagram of a spatial trivalent graph which represents the handlebody-link.

An IH-move is a local spatial move on spatial trivalent graphs as described in Figure 1, where the replacement is applied in a 3-ball embedded in $S^3$. Then we have the following theorem.

Theorem 1.1 ([6]). For spatial trivalent graphs $K_1$ and $K_2$, the following are equivalent.

- $K_1$ and $K_2$ represent an equivalent handlebody-link.
- $K_1$ and $K_2$ are related by a finite sequence of IH-moves.
- Diagrams of $K_1$ and $K_2$ are related by a finite sequence of the moves depicted in Figure 2.
2 A $G$-family of quandles

A quandle [12, 16] is a non-empty set $X$ with a binary operation $*: X \times X \to X$ satisfying the following axioms.

- For any $x \in X$, $x * x = x$.
- For any $x \in X$, the map $S_x : X \to X$ defined by $S_x(y) = y * x$ is a bijection.
- For any $x, y, z \in X$, $(x * y) * z = (x * z) * (y * z)$.

When we specify the binary operation $*$ of a quandle $X$, we denote the quandle by the pair $(X, *)$. An Alexander quandle $(M, *)$ is a $\Lambda$-module $M$ with the binary operation defined by $x * y = tx + (1 - t)y$, where $\Lambda := \mathbb{Z}[t, t^{-1}]$. A conjugation quandle $(G, *)$ is a group $G$ with the binary operation defined by $x * y = y^{-1}xy$.

Let $G$ be a group with identity element $e$. A $G$-family of quandles is a non-empty set $X$ with a family of binary operations $*^g : X \times X \to X (g \in G)$ satisfying the following axioms.

- For any $x \in X$ and any $g \in G$, $x *^g x = x$.
- For any $x, y \in X$ and any $g, h \in G$,
  \[ x *^{gh} y = (x *^g y) *^h y \text{ and } x *^e y = x. \]
- For any $x, y, z \in X$ and any $g, h \in G$,
  \[ (x *^g y) *^h z = (x *^h z) *^{h^{-1}gh} (y *^h z). \]
When we specify the family of binary operations \( *^g : X \times X \to X \ (g \in G) \) of a \( G \)-family of quandles, we denote the \( G \)-family of quandles by the pair \((X, \{ *^g \}_{g \in G})\).

**Proposition 2.1.** Let \( G \) be a group. Let \((X, \{ *^g \}_{g \in G})\) be a \( G \)-family of quandles.

(1) For each \( g \in G \), the pair \((X, *^g)\) is a quandle.

(2) We define a binary operation \( \triangleright : (X \times G) \times (X \times G) \to X \times G \) by
\[
(x, g) \triangleright (y, h) = (x *^h y, h^{-1}gh).
\]

Then \((X \times G, \triangleright)\) is a quandle.

We call the quandle \((X \times G, *)\) in Proposition 2.1 the associated quandle of \( X \).

**Example 2.2.** (1) Let \((X, \ast)\) be a quandle. Let \( S_x : X \to X \) be the bijection defined by \( S_x(y) = y \ast x \). Let \( m \) be a positive integer such that \( S_x^m = \text{id}_X \) for any \( x \in X \) if such an integer exists. We define the binary operation \( \ast^i : X \times X \to X \) by \( x \ast^i y = S_y^i(x) \). Then \( X \) is a \( \mathbb{Z} \)-family of quandles and a \( \mathbb{Z}_m \)-family of quandles, where \( \mathbb{Z}_m = \mathbb{Z}/m\mathbb{Z} \).

(2) Let \( R \) be a ring, and \( G \) a group with identity element \( e \). Let \( X \) be a right \( R[G] \)-module, where \( R[G] \) is the group ring of \( G \) over \( R \). We define the binary operation \( *^g : X \times X \to X \) by \( x *^g y = xg + y(e - g) \). Then \( X \) is a \( G \)-family of quandles.

### 3 Colorings

Let \( D \) be a diagram of a handlebody-link \( H \). We set an orientation for each edge in \( D \). Then \( D \) is a diagram of an oriented spatial trivalent graph \( K \). We may represent an orientation of an edge by a normal orientation, which is obtained by rotating a usual orientation counterclockwise by \( \pi/2 \) on the diagram. We denote by \( \mathcal{A}(D) \) the set of arcs of \( D \), where an arc is a piece of a curve each of whose endpoints is an undercrossing or a vertex. For an arc \( \alpha \) incident to a vertex \( \omega \), we define \( \epsilon(\alpha; \omega) \in \{1, -1\} \) by
\[
\epsilon(\alpha; \omega) = \begin{cases} 
1 & \text{if the orientation of } \alpha \text{ points to } \omega, \\
-1 & \text{otherwise.}
\end{cases}
\]

Let \( X \) be a \( G \)-family of quandles, and \( Q \) the associated quandle of \( X \). Let \( p_X \) (resp. \( p_G \)) be the projection from \( Q \) to \( X \) (resp. \( G \)). An \( X \)-coloring of \( D \) is a map \( C : \mathcal{A}(D) \to Q \) satisfying the following conditions at each crossing \( \chi \) and each vertex \( \omega \) of \( D \) (see Figure 3).

- Let \( \chi_1, \chi_2 \) and \( \chi_3 \) be respectively the under-arcs and the over-arc at a crossing \( \chi \).
such that the normal orientation of $\chi_3$ points from $\chi_1$ to $\chi_2$. Then
\[ C(\chi_2) = C(\chi_1) \triangleright C(\chi_3). \]

- Let $\omega_1, \omega_2, \omega_3$ be the arcs incident to a vertex $\omega$ arranged clockwise around $\omega$. Then
\[
\begin{align*}
(p_X \circ C)(\omega_1) &= (p_X \circ C)(\omega_2) = (p_X \circ C)(\omega_3), \\
(p_G \circ C)(\omega_1)^{e(\omega_1;\omega)}(p_G \circ C)(\omega_2)^{e(\omega_2;\omega)}(p_G \circ C)(\omega_3)^{e(\omega_3;\omega)} &= e.
\end{align*}
\]

We denote by $\text{Col}_X(D)$ the set of $X$-colorings of $D$. For two diagrams $D$ and $E$ which locally differ, we denote by $A(D, E)$ the set of arcs that $D$ and $E$ share.

**Lemma 3.1.** Let $X$ be a $G$-family of quandles. Let $D$ be a diagram of an oriented spatial trivalent graph. Let $E$ be a diagram obtained by applying one of the $R1$-$R6$ moves to the diagram $D$ once, where we choose orientations for $E$ which agree with those for $D$ on $A(D, E)$. For $C \in \text{Col}_X(D)$, there is a unique $X$-coloring $C_{D,E} \in \text{Col}_X(E)$ such that $C|_{A(D,E)} = C_{D,E}|_{A(D,E)}$.

**Remark 3.2.** Let $X$ be a $\mathbb{Z}$-family of quandles or a $\mathbb{Z}_m$-family of quandles defined as in Example 2.2 (2). Then an $X$-coloring be regarded as an $X$-coloring defined in [7].

Let $X$ be a $G$-family of quandles, and $Q$ the associated quandle of $X$. An $X$-set is a non-empty set $Y$ with a family of maps $*^g : Y \times X \to Y$ satisfying the following axioms, where we note that we use the same symbol $*^g$ as the binary operation of the $G$-family of quandles.

- For any $y \in Y$, $x \in X$, and any $g, h \in G$,
\[ y *^{gh} x = (y *^g x) *^h x \text{ and } y *^e x = y. \]
For any $y \in Y, x_1, x_2 \in X$, and any $g, h \in G$,

\[(y *^g x_1) *^h x_2 = (y *^h x_2) *^{h^{-1}gh} (x_1 *^h x_2).\]

Put $y \triangleright (x, g) := y *^g x$ for $y \in Y, (x, g) \in Q$. Then the second axiom implies that $(y \triangleright q_1) \triangleright q_2 = (y \triangleright q_2) \triangleright (q_1 \triangleright q_2)$ for $q_1, q_2 \in Q$. Any $G$-family of quandles $\{X, \{*^g\}_{g \in G}\}$ itself is an $X$-set with its binary operations. Any singleton set $\{y\}$ is also an $X$-set with the maps $*^g$ defined by $y *^g x = y$ for $x \in X$ and $g \in G$, which is a trivial $X$-set.

Let $D$ be a diagram of an oriented spatial trivalent graph. We denote by $R(D)$ the set of complementary regions of $D$. Let $X$ be a $G$-family of quandles, and $Y$ an $X$-set. Let $Q$ be the associated quandle of $X$. An $X_Y$-coloring of $D$ is a map $C : R(D) \cup R(D) \to Q \cup Y$ satisfying the following conditions.

- $C(\mathcal{A}(D)) \subset Q, C(\mathcal{R}(D)) \subset Y$.
- The restriction $C|_{\mathcal{A}(D)}$ of $C$ on $\mathcal{A}(D)$ is an $X$-coloring of $D$.
- For any arc $\alpha \in \mathcal{A}(D)$, we have

\[C(\alpha_1) \triangleright C(\alpha) = C(\alpha_2),\]

where $\alpha_1, \alpha_2$ are the regions facing the arc $\alpha$ so that the normal orientation of $\alpha$ points from $\alpha_1$ to $\alpha_2$ (see Figure 4).

We denote by $\text{Col}_X(D)_Y$ the set of $X_Y$-colorings of $D$.

For two diagrams $D$ and $E$ which locally differ, we denote by $R(D, E)$ the set of regions that $D$ and $E$ share.

**Lemma 3.3.** Let $X$ be a $G$-family of quandles, $Y$ an $X$-set. Let $D$ be a diagram of an oriented spatial trivalent graph. Let $E$ be a diagram obtained by applying one of the $R1$-$R6$ moves to the diagram $D$ once, where we choose orientations for $E$ which agree with those for $D$ on $\mathcal{A}(D, E)$. For $C \in \text{Col}_X(D)_Y$, there is a unique $X_Y$-coloring $C_{D, E} \in \text{Col}_X(E)_Y$ such that $C|_{\mathcal{A}(D, E)} = C_{D, E}|_{\mathcal{A}(D, E)}$ and $C|_{\mathcal{R}(D, E)} = C_{D, E}|_{\mathcal{R}(D, E)}$. 

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**Figure 4:**

- For any $y \in Y, x_1, x_2 \in X$, and any $g, h \in G$,
4 A homology

Let $X$ be a $G$-family of quandles, and $Y$ an $X$-set. Let $(Q, \triangleright)$ be the associated quandle of $X$. Let $B_n(X)_Y$ be the free abelian group generated by the elements of $Y \times Q^n$ if $n \geq 0$, and let $B_n(X)_Y = 0$ otherwise. We put

$$(y, q_1, \ldots, q_i) \triangleright q, q_{i+1}, \ldots, q_n) := (y \triangleright q, q_1 \triangleright q, \ldots, q_i \triangleright q, q_{i+1}, \ldots, q_n)$$

for $y \in Y$ and $q, q_1, \ldots, q_n \in Q$. We define a boundary homomorphism $\partial_n : B_n(X)_Y \to B_{n-1}(X)_Y$ by

$$\partial_n(y, q_1, \ldots, q_n) = \sum_{i=1}^{n} (-1)^i (y, q_1, \ldots, q_{i-1}, q_{i+1}, \ldots, q_n)$$

for $n > 0$, and $\partial_n = 0$ otherwise. Then $B_\ast(X)_Y = (B_n(X)_Y, \partial_n)$ is a chain complex (see [1, 2, 4, 5]).

Let $D_n(X)_Y$ be the subgroup of $B_n(X)_Y$ generated by the elements of

$$\bigcup_{i=1}^{n-1} \{(y, q_1, \ldots, q_{i-1}, (x, g), (x, h), q_{i+2}, \ldots, q_n) \mid y \in Y, x \in X, g, h \in G \}$$

and

$$\bigcup_{i=1}^{n} \{-(y, q_1, \ldots, q_{i-1}, (x, g), q_{i+1}, \ldots, q_n) \mid y \in Y, x \in X, g, h \in G \}.$$

We remark that

$$(y, q_1, \ldots, q_{i-1}, (x, e), q_{i+1}, \ldots, q_n)$$

and

$$(y, q_1, \ldots, q_{i-1}, (x, g), q_{i+1}, \ldots, q_n)$$

$$(y, q_1, \ldots, q_{i-1}, (x, g), q_{i+1}, \ldots, q_n)$$

belong to $D_n(X)_Y$.

**Lemma 4.1.** For $n \in \mathbb{Z}$, we have $\partial_n(D_n(X)_Y) \subset D_{n-1}(X)_Y$. Thus $D_\ast(X)_Y = (D_n(X)_Y, \partial_n)$ is a subcomplex of $B_\ast(X)_Y$.

We put $C_n(X)_Y = B_n(X)_Y/D_n(X)_Y$. Then $C_\ast(X)_Y = (C_n(X)_Y, \partial_n)$ is a chain complex. For an abelian group $A$, we define the cochain complex $C^\ast(X; A)_Y = \text{Hom}(C_\ast(X)_Y, A)$. We denote by $H_n(X)_Y$ the $n$th homology group of $C_\ast(X)_Y$. 
5 Cocycle invariants

Let $X$ be a $G$-family of quandles, and $Y$ an $X$-set. Let $D$ be a diagram of an oriented spatial trivalent graph. For an $X_Y$-coloring $C \in \text{Col}_X(D)_Y$, we define the weight $w(\chi; C) \in C_2(X)_Y$ at a crossing $\chi$ of $D$ as follows. Let $\chi_1, \chi_2$ and $\chi_3$ be respectively the under-arcs and the over-arc at a crossing $\chi$ such that the normal orientation of $\chi_3$ points from $\chi_1$ to $\chi_2$. Let $R_\chi$ be the region facing $\chi_1$ and $\chi_3$ such that the normal orientations $\chi_1$ and $\chi_3$ point from $R_\chi$ to the opposite regions with respect to $\chi_1$ and $\chi_3$, respectively. Then we define

$$w(\chi; C) = \epsilon(\chi)(C(R_\chi), C(\chi_1), C(\chi_3)),$$

where $\epsilon(\chi) \in \{1, -1\}$ is the sign of a crossing $\chi$. We define a chain $W(D; C) \in C_2(X)_Y$ by

$$W(D; C) = \sum_{\chi} w(\chi; C),$$

where $\chi$ runs over all crossings of $D$.

**Lemma 5.1.** The chain $W(D; C)$ is a 2-cycle of $C_*(X)_Y$. Further, for cohomologous 2-cocycles $\theta, \theta'$ of $C^*(X; A)_Y$, we have $\theta(W(D; C)) = \theta'(W(D; C))$.

**Lemma 5.2.** Let $D$ be a diagram of an oriented spatial trivalent graph. Let $E$ be a diagram obtained by applying one of the $R1$-$R6$ moves to the diagram $D$ once, where we choose orientations for $E$ which agree with those for $D$ on $A(D, E)$. For $C \in \text{Col}_X(D)_Y$ and $C_{D,E} \in \text{Col}_X(E)_Y$ such that $C|_{A(D,E)} = C_{D,E}|_{A(D,E)}$ and $C|_{R(D,E)} = C_{D,E}|_{R(D,E)}$, we have $[W(D; C)] = [W(E; C_{D,E})] \in H_2(X)_Y$.

We denote by $G_H$ (resp. $G_K$) the fundamental group of the exterior of a handlebody-link $H$ (resp. a spatial graph $K$). When $H$ is represented by $K$, the groups $G_H$ and $G_K$ are identical. Let $D$ be a diagram of an oriented spatial trivalent graph $K$. By the definition
of an $X_Y$-coloring $C$ of $D$, the map $p_G \circ C|_{A(D)}$ represents a homomorphism from $G_K$ to $G$, which we denote by $\rho_C \in \text{Hom}(G_K, G)$. For $\rho \in \text{Hom}(G_K, G)$, we define
\[
\text{Col}_X(D; \rho)_Y = \{ C \in \text{Col}_X(D)_Y \mid \rho_C = \rho \}.
\]
For a 2-cocycle $\theta$ of $C^*(X; A)_Y$, we define
\[
\mathcal{H}(D) := \{ [W(D; C)] \in H_2(X)_Y \mid C \in \text{Col}_X(D)_Y \},
\]
\[
\Phi_{\theta}(D) := \{ \theta(W(D; C)) \in A \mid C \in \text{Col}_X(D)_Y \},
\]
\[
\mathcal{H}(D; \rho) := \{ [W(D; C)] \in H_2(X)_Y \mid C \in \text{Col}_X(D; \rho)_Y \},
\]
\[
\Phi_{\theta}(D; \rho) := \{ \theta(W(D; C)) \in A \mid C \in \text{Col}_X(D; \rho)_Y \}
\]
as multisets.

**Lemma 5.3.** Let $D$ be a diagram of an oriented spatial trivalent graph $K$. For $\rho, \rho' \in \text{Hom}(G_K, G)$ such that $\rho$ and $\rho'$ are conjugate, we have $\mathcal{H}(D; \rho) = \mathcal{H}(D; \rho')$ and $\Phi_{\theta}(D; \rho) = \Phi_{\theta}(D; \rho')$.

We denote by $\text{Conj}(G_K, G)$ the set of conjugacy classes of homomorphisms from $G_K$ to $G$. By Lemma 5.3, $\mathcal{H}(D; \rho)$ and $\Phi_{\theta}(D; \rho)$ are well-defined for $\rho \in \text{Conj}(G_K, G)$.

**Lemma 5.4.** Let $D$ be a diagram of an oriented spatial trivalent graph $K$. Let $E$ be a diagram obtained from $D$ by reversing the orientation of an edge $e$. For $\rho \in \text{Hom}(G_K, G)$, we have $\mathcal{H}(D) = \mathcal{H}(E)$, $\Phi_{\theta}(D) = \Phi_{\theta}(E)$, $\mathcal{H}(D; \rho) = \mathcal{H}(E; \rho)$ and $\Phi_{\theta}(D; \rho) = \Phi_{\theta}(E; \rho)$.

By Lemma 5.4, $\mathcal{H}(D)$, $\Phi_{\theta}(D)$, $\mathcal{H}(D; \rho)$ and $\Phi_{\theta}(D; \rho)$ are well-defined for a diagram $D$ of an unoriented spatial trivalent graph, which is a diagram of a handlebody-link. For a diagram $D$ of a handlebody-link $H$, we define
\[
\mathcal{H}_{\text{hom}}(D) := \{ \mathcal{H}(D; \rho) \mid \rho \in \text{Hom}(G_H, G) \},
\]
\[
\Phi_{\theta, \text{hom}}(D) := \{ \Phi_{\theta}(D; \rho) \mid \rho \in \text{Hom}(G_H, G) \},
\]
\[
\mathcal{H}_{\text{conj}}(D) := \{ \mathcal{H}(D; \rho) \mid \rho \in \text{Conj}(G_H, G) \},
\]
\[
\Phi_{\theta, \text{conj}}(D) := \{ \Phi_{\theta}(D; \rho) \mid \rho \in \text{Conj}(G_H, G) \}
\]
as "multisets of multisets". We remark that, for $X_Y$-colorings $C$ and $C_{D,E}$ in Lemma 5.2, we have $\rho_C = \rho_{C_{D,E}}$. Then, by Lemmas 5.1–5.4, we have the following theorem.
Theorem 5.5. Let $X$ be a $G$-family of quandles, $Y$ an $X$-set. Let $\theta$ be a 2-cocycle of $C^*(X;A)_Y$. Let $H$ be a handlebody-link represented by a diagram $D$. Then the following are invariants of a handlebody-link $H$.

$$\mathcal{H}(D), \Phi_\theta(D), \mathcal{H}^{\text{hom}}(D), \Phi_\theta^{\text{hom}}(D), \mathcal{H}^{\text{conj}}(D), \Phi_\theta^{\text{conj}}(D).$$

We denote the invariants of $H$ given in Theorem 5.5 by

$$\mathcal{H}(H), \Phi_\theta(H), \mathcal{H}^{\text{hom}}(H), \Phi_\theta^{\text{hom}}(H), \mathcal{H}^{\text{conj}}(H), \Phi_\theta^{\text{conj}}(H),$$

respectively.

We denote by $H^*$ the mirror image of a handlebody-link $H$. Then we have the following theorem.

Theorem 5.6. For a handlebody-link $H$, we have

$$\mathcal{H}(H^*) = -\mathcal{H}(H), \quad \Phi_\theta(H^*) = -\Phi_\theta(H),$$

$$\mathcal{H}^{\text{hom}}(H^*) = -\mathcal{H}^{\text{hom}}(H), \quad \Phi_\theta^{\text{hom}}(H^*) = -\Phi_\theta^{\text{hom}}(H),$$

$$\mathcal{H}^{\text{conj}}(H^*) = -\mathcal{H}^{\text{conj}}(H), \quad \Phi_\theta^{\text{conj}}(H^*) = -\Phi_\theta^{\text{conj}}(H),$$

where $-S = \{-a \mid a \in S\}$ for a multiset $S$.

6 Applications

In this section, we calculate cocycle invariants defined in the previous section for the handlebody-knots $0_1, \ldots, 6_{16}$ in the table given in [9], by using a 2-cocycle given by Nosaka [18]. This calculation enables us to distinguish some of handlebody-knots from their mirror images, and a pair of handlebody-knots whose complements have isomorphic fundamental groups.

Let $G = SL(2;\mathbb{Z}_3)$ and $X = (\mathbb{Z}_3)^2$. Then $X$ is a $G$-family of quandles with the proper binary operation as given in Proposition 2.2 (2). Let $Y$ be the trivial $X$-set $\{y\}$. We define a map $\theta : Y \times (X \times G)^2 \to \mathbb{Z}_3$ by

$$\theta(y, (x_1, g_1), (x_2, g_2)) := \lambda(g_1) \det(x_1 - x_2, x_2(1 - g_2^{-1})), $$

where the abelianization $\lambda : G \to \mathbb{Z}_3$ is given by

$$\lambda \begin{pmatrix} a & b \\ c & d \end{pmatrix} = (a + d)(b - c)(1 - bc).$$
By [18], the map $\theta$ is a 2-cocycle of $C^*(X;\mathbb{Z}_3)_Y$. Table 1 lists the invariant $\Phi_{\theta}^{\text{conj}}(H)$ for the handlebody-knots $0_1, \ldots, 6_{16}$. We represent the multiplicity of elements of a multiset by using subscripts. For example, $\{(0_2, 1_3), (0_3)\}$ represents the multiset $\{0, 0, 1, 1, 1\}, \{0, 0, 0\}, \{0, 0, 0\}$.

From Table 1, we see that our invariant can distinguish the handlebody-knots $6_{14}, 6_{15}$, whose complements have the isomorphic fundamental groups. Together with Theorem 5.6, we also see that handlebody-knots $5_2, 5_3, 6_5, 6_9, 6_{11}, 6_{12}, 6_{13}, 6_{14}, 6_{15}$ are not equivalent to their mirror images. In particular, the chiralities of $5_3, 6_5, 6_{11}$ and $6_{12}$ were not known. Table 2 shows us known facts on the chirality of handlebody-knots in [9] so far. In the column of "chirality", the symbols $\bigcirc$ and $\times$ mean that the handlebody-knot is amphichiral and chiral, respectively, and the symbol $?$ means that it is not known whether the handlebody-knot is amphichiral or chiral. The symbols $\checkmark$ in the right five columns mean that the handlebody-knots can be proved chiral by using the method introduced
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表 2:

in the papers corresponding to the columns. Here, M, II, LL, IKO and IIJO denote the papers [17], [7], [15], [10] and this paper, respectively.

References


http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.65.3250

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